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LINEARLY POLARIZED DUAL-WAVELENGTH VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING LASER (Postprint)

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14. ABSTRACT
The authors demonstrate the multiwatt linearly polarized dual-wavelength operation in an optically pumped vertical-external-cavity surface-emitting laser by means of an intracavity tilted Fabry-Perot etalon and a Brewster window. The sum frequency generation from the lithium triborate crystal pumped by this laser confirms that these two wavelengths oscillate simultaneously. Over 30 dB side-mode suppression can be achieved at dual wavelengths with a spectral spacing of 2.1 nm. The output power is slightly reduced by the intracavity Fabry-Perot etalon and Brewster window.

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Linearly polarized dual-wavelength vertical-external-cavity surface-emitting laser

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The authors demonstrate the multiwatt linearly polarized dual-wavelength operation in an optically pumped vertical-external-cavity surface-emitting laser by means of an intracavity tilted Fabry-Perot etalon and a Brewster window. The sum frequency generation from the lithium triborate crystal pumped by this laser confirms that these two wavelengths oscillate simultaneously. Over 30 dB side-mode suppression can be achieved at dual wavelengths with a spectral spacing of 2.1 nm. The output power is slightly reduced by the intracavity Fabry-Perot etalon and Brewster window. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2735554]

Dual-wavelength lasers are required for a variety of applications. The attempt to achieve a dual-wavelength (~984 and ~1042 nm) vertical-external-cavity surface-emitting laser (VECSEL) was conducted recently.[1] This laser is based on a complicated design and a critical epitaxial growth of the VECSEL chip. However, its lasing spectrum at each color is a few nanometer wide and the laser also indicates self-pulsation.

It is possible for a traditional VECSEL (Ref. 2) to simultaneously lase at dual wavelengths separated by a few nanometers. First, the quantum well gain spectra have a wide bandwidth with a relatively flat peak. Second, the VECSEL gain medium is inhomogeneously broadened due to the electron-phonon interaction, the width and composition fluctuations in multiquantum wells, as well as material defects.[3] In addition, an external cavity of a few centimeters results in very dense longitudinal modes. All of these result in low longitudinal mode selectivity of the VECSEL; thus, high-power VECSEL tends to oscillate in multilongitudinal modes with an envelope of a few nanometers.[4,5] Dynamically, stable two-wavelength oscillation of a laser can occur when the mode coupling between two wavelengths is weak.[6,7] Therefore, using a suitable intracavity filter, one may realize dual-wavelength oscillation in a regular VECSEL.

In this letter, we proposed and demonstrated a linearly polarized dual-wavelength VECSEL by means of a tilted intracavity Fabry-Perot (FP) etalon and a Brewster window. The proper free spectral range of the tilted étalon allows the VECSEL to oscillate at two wavelengths simultaneously.

The VECSEL structure, designed for emission around 975 nm, was grown by metal-organic vapor phase epitaxy on an undoped GaAs substrate. The active region consists of 14 InGaAs compressive strained quantum wells. Each quantum well is 8 nm thick and surrounded by (~31 nm thick) GaAsP strain compensation layers and AlGaAs pump-absorbing barriers. The thickness and composition of the layers are optimized such that each quantum well is positioned at an antinode of the cavity standing wave to provide resonant periodic gain (RPG). A high-reflectivity ($R > 99.9\%$) distributed Bragg reflector (DBR) stack made of 25 pairs of $Al_{0.2}Ga_{0.8}As/AlAs$ is grown on the top of the active region. In addition to the RPG active region and DBR stack, there is a high aluminum concentration AlGaAs etch-stop layer between the active region and the substrate to facilitate selective chemical substrate removal. The epitaxial side of the VECSEL wafer was mounted on chemical vapor deposited diamond by indium solder. After the removal of the GaAs substrate and etch-stop layer, a single layer Si_3N_4 ($n = 1.78$ at 980 nm) quarter-wave low-reflection (LR) coating (for 975 nm signal) was deposited on the surface of the VECSEL chip to achieve a reflectance of less than 1% at the signal wavelength. Also, this coating significantly reduces the reflectance of 808 nm pump emission at the chip surface.

The experimental setup is shown in Fig. 1. A *V*-shaped cavity which is folded at the VECSEL chip is used in the experiment, allowing a double-pass through the gain region, thus increasing efficiency.[5] Unfolding the cavity about the DBR mirror, one can view the active region of the VECSEL chip as a tilted intracavity FP étalon. The previously mentioned LR coating reduces walk-off loss.[8] The processed VECSEL chip was mounted on a heat sink for temperature control. The lasing experiment was conducted by using a fiber coupled multimode 808 nm diode laser pump source. A 480 μm diameter pump spot was focused on the VECSEL

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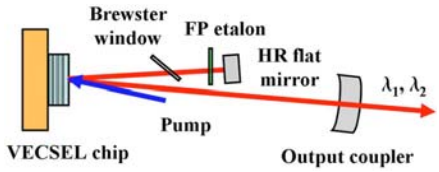

FIG. 1. (Color online) Schematic diagram of a linearly polarized dual-wavelength VECSEL with the *V*-shaped cavity, a Brewster window, and an intracavity tilted FP étalon. Relative dimensions are not to scale.

chip during the experiment. In the *V*-shaped cavity, the distance between the high-reflecting (HR) ($R > 99.9\%$ at signal wavelength) flat mirror and the chip is around 6 cm and the distance between the chip and the output coupler ($R \sim 97\%$ at signal wavelength, 30 cm radius of curvature) is about 20.5 cm. The size of TEM_{00} mode on the VECSEL chip is about 425 μm diameter, matching the pump spot size of 480 μm diameter. The cavity angle between two arms of the *V*-shaped cavity is about 8°, resulting in the refraction angle in the semiconductor to be less than 1.3°. Such a small refraction angle does not significantly change the relative confinement factor. Both a FP étalon and a Brewster window, which are $\sim$150 μm thick uncoated commercial glass slides, were inserted between the chip and the HR flat mirror to achieve linearly polarized dual-wavelength VECSEL. By scanning the glass slide in an expanded and collimated He–Ne laser beam and monitoring the interference fringes on a shear plate, we selected the desired area on the glass slide, in which both sides of the glass slide are parallel and smooth. This area was aligned in the cavity to cross the laser beam. The free spectral range of the filter is about 0.67 THz (or 2.0 nm).

The pump spot on the chip plays a role as an aperture. Since the Gaussian beam suffers from the distortion introduced by a tilted FP étalon,[8] this distorted laser beam in conjunction with the aperture causes more diffraction loss due to the truncation of the aperture. In the experiment we observed that inserting the étalon in the longer arm of the *V*-shaped cavity causes lower efficiency of the laser (i.e., much more diffraction loss into the VECSEL) than placing them in the short arm.

Figure 2 shows the lasing spectra with/without both the intracavity tilted étalon and Brewster window. During the measurement, the temperature of the heat sink was fixed at 10 °C. The lasing spectral intensity (in dBm) at 16.4 W pump power is shown in Fig. 2(a). Figures 2(b) and 2(c) show the lasing spectral intensity (in dBm and linear scale, respectively) at 26.5 W pump power. At these two pump levels, without the étalon and Brewster window, the VECSEL lasing spectra [black solid lines in Figs. 2(a) and 2(b)] are a few nanometer wide and shift with the increase of the pump power. After the étalon and Brewster window were inserted in the cavity, as illustrated in Fig. 1, the étalon was properly tilted such that the spectral intensity of each color was even and the total output power was optimized. The dual-wavelength lasing spectra selected by the étalon [red solid line in Figs. 2(a) and 2(b)] indicate over 30 dB side-mode suppression. Additionally, the dual-wavelength lasing spectra indicate similar redshift behavior as the unfiltered lasing spectra. The dual-wavelength lasing spectrum (in linear scale) in Fig. 2(c) gives the linewidth (full width at half maximum) of $\sim$0.5 nm for each color and the spectral spacing of 2.1 nm. Due to the lack of a suitable grating to separate these two wavelengths, we could not directly measure the power of each wavelength. Since the spectral intensity is even at two wavelengths, the power of each wavelength should be close to each other. The penalty for using intracavity components is the loss of laser efficiency. At 26.5 W pumping, the output powers are 4.78 W (free lasing), 4.5 W (after inserting FP étalon), and 3.98 W (after inserting both FP étalon and Brewster window), respectively. The intracavity FP étalon and Brewster window only reduce the total output power by 17% at this pump level.

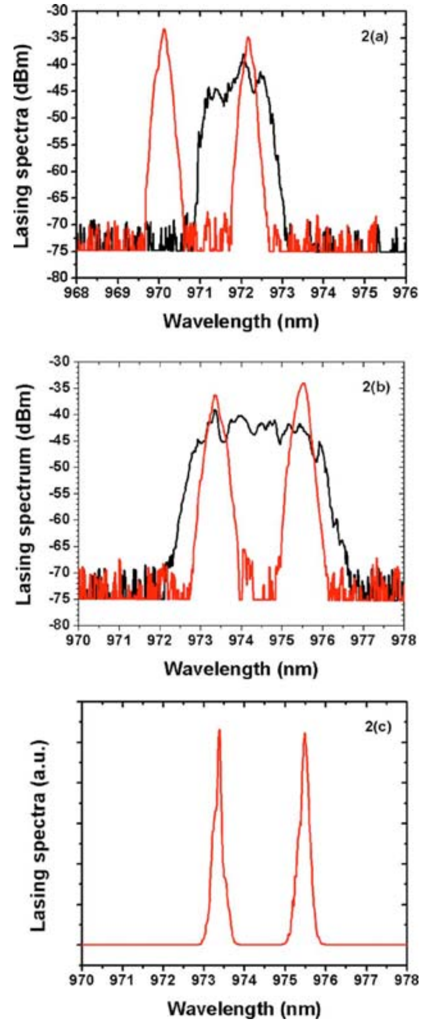

FIG. 2. (Color online) Lasing spectra without/with a tilted intracavity FP étalon (black/red solid line) at 16.4 W pump (a) and 26.5 W pump [(b) and (c)].

To confirm that the VECSEL oscillates at these two wavelengths simultaneously, we focused the collinear dual-wavelength output into the type-I angle phase-matched lithium triborate crystal, employed to generate tunable second harmonic generation (SHG) around 488 nm,[9] to generate sum frequency generation (SFG). Since the two wavelengths (λ_1 and λ_2) are only separated by 2.1 nm, the phase matching angle for SFG of λ_1 and λ_2 is also close to that of SHG of λ_1 or λ_2. These three nonlinear conversion signals should be observed. Figure 3 shows the SFG (central peak) as well as

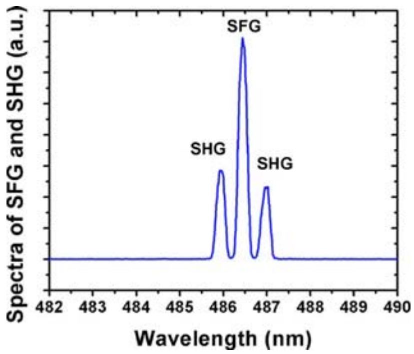

FIG. 3. (Color online) Spectra of extracavity sum frequency generation (SFG) of dual wavelengths of the VECSEL and second harmonic generation (SHG) of each fundamental wavelength.

the SHG of each fundamental wavelength (side peaks, separated by ~1 nm). The SFG signal confirms that these two wavelengths lase simultaneously.

Some practical drawbacks of this linearly polarized dual-wavelength VECSEL must be mentioned. The spectral intensity at these two wavelengths is not always even. We observed that each of these two spectral peaks in Fig. 2(c) became dominant slowly and alternately due to the longitudinal mode competition between them. Meanwhile, dual-wavelength output power slowly fluctuated in the range of ±50 mW. Stabilizing this dual-wavelength operation is the subject of ongoing work.

In summary, employing an intracavity tilted FP étalon and a Brewster window is a simple and efficient method to realize a linearly polarized, simultaneously dual-wavelength oscillation in a traditional VECSEL. At multiple watts of dual-wavelength VECSEL output, over 30 dB side-mode suppression was demonstrated at two wavelengths, separated by ~2.1 nm. The loss of output power caused by the FP étalon and Brewster window is less than 17%.

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